

# Active Flow Control Using MEMS

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## SUMMARY

*This lecture presents an overview of the potential for the application of MEMS for the active control of fluid flows. In addition to providing a general overview of the underlying fluid mechanics and status of current research the relevance of this technology application to future military vehicle technologies is highlighted. The lecture identifies the potential benefits of the use of MEMS for controlling flow separation and reducing drag on a range of air vehicles and their propulsion systems. Because of the overview nature of this lecture the material presented has been extracted from a wide range of public domain sources both in the USA and Europe. Where, possible such material has been attributed to its originator. Apologies are made in circumstances where attributions have not been made.*

## 1.0 INTRODUCTION

The performance, observability and affordability of most military vehicles are influenced by fluid physics either directly by their interaction with the surrounding air/water or indirectly through the many fluidic based systems they incorporate. The ability to manipulate a fluid flow to improve efficiency or performance is of immense technological importance and is currently one of the most high profile topics in fluid dynamics. The potential benefits of flow control include improved performance and manoeuvrability, affordability, increased range and payload, and environmental compliance. The intent of flow control may be to delay/advance transition, to suppress/enhance turbulence, or to prevent/promote separation. The resulting benefits include drag reduction, lift enhancement, mixing augmentation, heat transfer enhancement, and the suppression of flow-induced noise.

The desire to minimise drag (both skin friction and pressure) and to control flow separation in order to improve the high lift and propulsive performance of a wide range of vehicles is providing a driver for increased research activity in this field. In most cases drag and flow separation is dominated by the thin layer of fluid (often just a few millimetres thick), known as the boundary layer, that forms at the interface between the vehicle's components and the surrounding fluid. Over the last 20 years or so our knowledge about the evolution and propagation of boundary layers has increased significantly. This has been made possible through the advent of new experimental techniques and the development and use of computation tools such as Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS). Developments of new manufacturing technologies such as Microfabricated Electro-Mechanical Systems (MEMS) and solid state actuator technologies such as piezo-electric materials and shape-memory alloys has also led to the possibility for active flow control to be realised at both a macro and micro scale.

MEMS technology offers the potential for the large-scale active control of coherent flow structures within the boundary layer. This could lead to the reduction of skin friction drag or the postponement of flow separation through the use of 'smart skins' capable of detecting and reacting to the state of the local boundary layer.

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27-28 February 2003; Monterey, CA, USA, 3-4 March 2003, and published in RTO-EN-AVT-105.*

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Despite over a century of intensive research, turbulence remains largely an enigma that is analytically unapproachable yet practically very important. The mysteries of turbulence are only now being solved by the use of physical and numerical experiments, which is a far-from-trivial task at the high Reynolds numbers of practical interest to the aerospace engineer. Controlling a practical turbulent flow to achieve a desired effect such as drag reduction, lift enhancement or noise reduction is a very difficult task. Passive control methods, while always preferable, are generally limited in their utility. Brute force suppression, or taming, of turbulence via active, energy consuming control devices is always possible, but the penalty for doing so often exceeds any potential savings. The challenge is to actively achieve a desired effect with a minimum of energy expenditure by utilising the natural instabilities within the fluid structures to amplify control inputs.

## **2.0 THE NATURE OF TURBULENCE**

Shear flow turbulence is dominated by a quasi-periodic sequence of large-scale structures often referred to as *turbulent coherent structures*. Coherent structures are not only quasi-periodic, but are different in size and shape depending on the location of these structures within the flow. Furthermore, the coherent structures are born, grow and die within the boundary layer, evolving in both space and time. The precise dynamics involved in the turbulence activities are far from clear. Qualitatively, according to the generally accepted school of thought, the process starts with pairs of elongated, counter rotating, stream-wise vortices buried within the near-wall sub-layer region. These vortices are often referred to as ‘hairpin’ vortices and arise in the first instance during the latter, non-linear stages of transition from laminar to turbulent flow. These hairpin vortices exist within a strong shear layer and induce low and high-speed regions between them. The low speed regions, close to the wall, termed *streaks*, grow downstream and develop inflectional velocity profiles. At the same time, the interface between the low and high-speed fluid begins to oscillate, signalling the onset of a secondary instability. The low speed region lifts up away from the wall as the oscillation amplitude increases and the flow rapidly breaks down (*bursts*) into a completely chaotic motion. In the sequence of turbulent activities within the boundary layer, there are two important events for energy production, called *sweeps* (or intrushes) and ejections (*bursts*). Over 80% of the turbulent kinetic energy production occurs during these events. The process described above is self-regenerating resulting in the continuous cyclic propagation of near near-wall hairpin vortices, streaks and bursts. There is still much speculation concerning the relationship between the stream-wise vortices and the streaks and significant further research in this field is required.

Large peaks in turbulent wall-shear stress are produced between a pair of counter-rotating longitudinal vortices as the high momentum fluid is brought down towards the wall during the near-wall burst events. These shear stress peaks give rise to the large increases in skin friction drag associated with a turbulent boundary layer compared to one that is laminar (typically an order of magnitude greater). Most of the activity in turbulent drag-reduction and separation control, both passive and active, relies on the manipulation by suppression, enhancement or modification of coherent turbulence structures.

## **3.0 ACTIVE FLOW CONTROL USING MEMS**

At the present time MEMS and turbulence control are seen as the “Holy Grail” of fluid mechanics. One potential application for MEMS technology is the control of fluid flows through the active manipulation of the coherent structures that develop in a boundary layer.

Various methods of flow control have been implemented in practical engineering situations using conventional technologies (suction, tangential blowing, riblets, and vortex generators). However, all of the technologies applied can be considered as either passive or at most open-loop control by the addition of energy. Not all of these technologies are entirely effective at the efficient control of either free-shear layer or turbulent wall bounded flows. There have also been severe limitations as to the efficiency of

conventional flow control technologies. For example, in attempting to reduce skin friction drag by suction (hybrid laminar flow) the penalties (weight, energy expenditure, and cost) associated with the control technology often exceed the benefits derived from its use. A way is needed to reduce the penalties and increase the benefits in order to achieve a more efficient control strategy.

Flow control is most efficient when applied at a region of the flow where susceptibility is high. i.e. in the critical regimes of the flow where flow instabilities magnify rapidly. The regions of boundary layer transition and flow separation are such areas. Therefore the delay/advancement of laminar to turbulent transition and the prevention/suppression of flow separation are relatively easy tasks to achieve. The reduction of skin friction in a stable, non-separating turbulent boundary layer is a much more difficult task. New ideas for turbulent flow control are based on the manipulation of the coherent structures that develop close to the wall. On practical engineering products such as the wings of aircraft and in the nacelles and components of their engines these flow structures occur at scales of tens to hundreds of microns. Technologies such as riblets can affect the near-wall turbulence generation process to achieve skin friction drag reductions of the order of 8 to 12%. However, newer ideas for turbulent flow control employing active MEMS scale technologies, giving potential reductions in skin friction drag of 50% or more have been spurred on by recent developments in the understanding of boundary layer physics, chaos control and fabrication technologies. Futuristic concepts are envisioned where large arrays of inexpensive, intelligent, interactive flow sensors and actuators are built into aerodynamic surfaces to interact with the organised flow structures that occur randomly in the boundary layer to achieve efficient control of the flow.

Research into the application of MEMS for flow control has been ongoing in the USA for a number of years. Significant activity exists at a number of US universities where financial support from the Government via the AFOSR and DARPA among others, is being directed. Recent experiments and simulations in the USA have demonstrated the fundamental feasibility of active boundary layer control. Europe is also involved in a number of activities to study the potential of MEMS for active flow control. These activities involve both academic and industrial organisations. Most European research activities revolve around the promotion or delay of flow separation since this is perceived as being realisable within a much nearer timeframe than turbulent drag reduction. In addition to the issues of the fabrication and application of sensor and actuator technologies studies are also ongoing to develop optimum control strategies and to develop design and analysis tools.

## **4.0 CONCLUDING REMARKS**

Although there are important activities going on to investigate the application of new technologies such as MEMS for active flow control it is unlikely that any will be mature for application, other than as a component of very simple systems, within the next decade or two.

Whether or not any of the flow control technologies will see a widespread application on a production aircraft in the future depends on two important factors:


- Does it work?
- Does it make practical economic sense?

The first question is probably the easiest criteria to address. In the first instance any new technology has to be demonstrated experimentally at large scale under relevant Reynolds and Mach numbers. It must then be proven to operate in the presence of real world conditions and shown to enhance or improve a valuable performance metric. Any system must be demonstrated to be manufacturable, robust, reliable, maintainable and inspectable. Any performance side effects must be acceptable.

The second criterion is more difficult to assess and the answer may change with evolving worldwide economic market and political conditions. To be viable any flow control application must have a favourable overall cost/benefit. The initial design/integration cost combined with the cost of energy expenditure during operation must be outweighed by any benefits obtained. Issues related to the legal/regulatory standpoints of product liability, safety, and environmental/acoustic pollution also need to be resolved.

Although many flow control technologies have been identified and researched at the basic level for many decades few have ever reached maturity and full-scale deployment on a commercial product. It could be argued that the basic research community is not sufficiently aware of the practical issues of implementation and that in some cases non-application useful research is carried out while in other areas the research is not carried far enough to allow technological evaluation. With the limited research investment available it is becoming essential that the research community work more closely with the application community to develop practical technologies in the most efficient manner. This requires all involved to work in a multidisciplinary environment to develop the basic tools and understanding and then to progress this towards large-scale demonstration and evaluation. It is important that unworkable concepts are filtered at the earliest possible opportunity in order to avoid unnecessary effort being directed at hopeless causes. Early in the assessment process it is essential that industrial studies be made to identify the potential benefits and practical implications of any new flow control technology. In order to do this industry requires robust, rapid tools with which to undertake aerodynamic analysis.

Turbulent flow control should not just be considered as a fix to solve a problem or a means of improving even further the performance of an already optimised design. Consideration should be given to employing turbulent flow control early in the design optimisation process. A commercially better design may be obtained by the use of flow control to recoup performance losses associated with simplifying other aspects of the design to reduce manufacturing costs, system complexity or structural weight (e.g., reduced sweep, thicker wings, smaller, simpler high lift systems).



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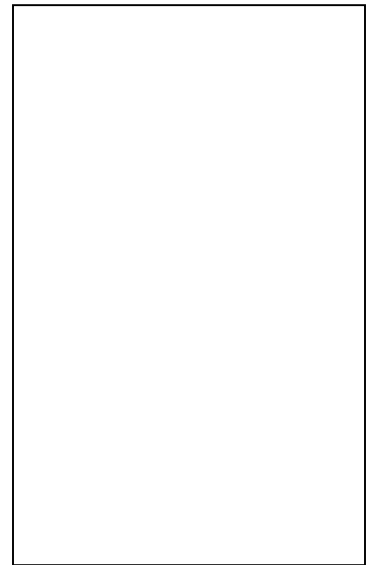
# RTO

## AVT Lecture Series 235

### MEMS Aerospace Applications

### Micro Flow Control (1)

Dr. Clyde Warsop



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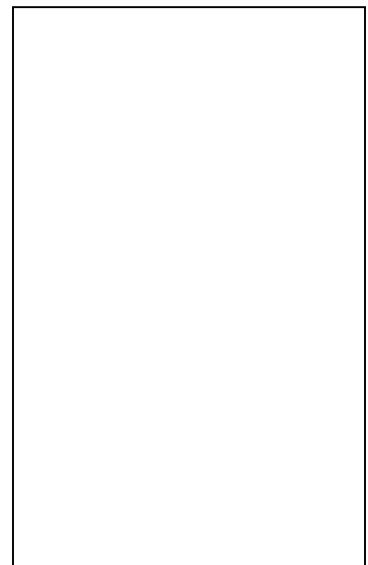
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### Lecture Outline

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- Introduction
  - What is it micro flow control about?
  - Why do we want to do it?
- Potential applications
- State-of-the-art
- Barriers to success



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## What is Micro Flow Control?

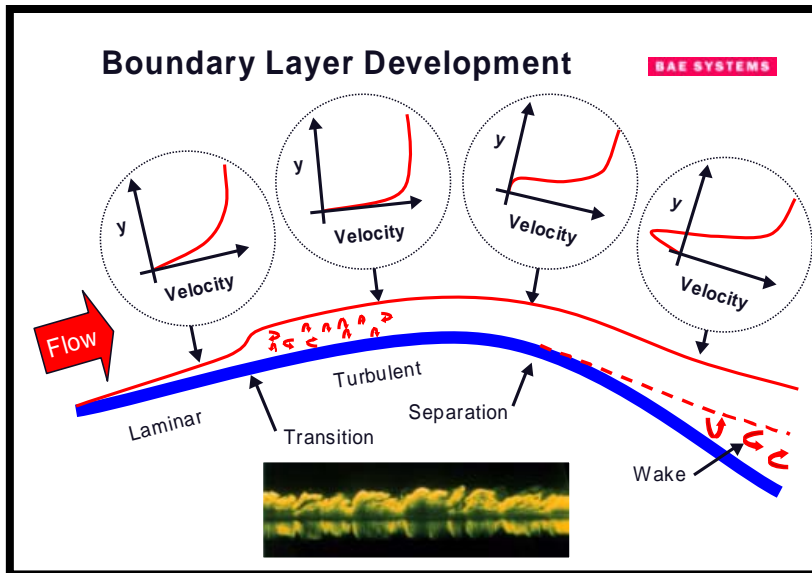
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- Manipulation of a fluid flow to effect a desired change leading to a practical benefit
  - Flow control is not new – it's what Aero/hydrodynamics has always been about
  - Reduce Drag
  - Delay/promote flow separation
  - Enhance mixing

## Engineering Relevance

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- External interactions of all vehicles with external fluids (air, water)
- Flows associated with propulsion systems, turbomachinery and IC engines (intakes, fans, compressors, combustion, turbines, exhausts)
- Fluid systems (pneumatics, cooling, hydraulics)




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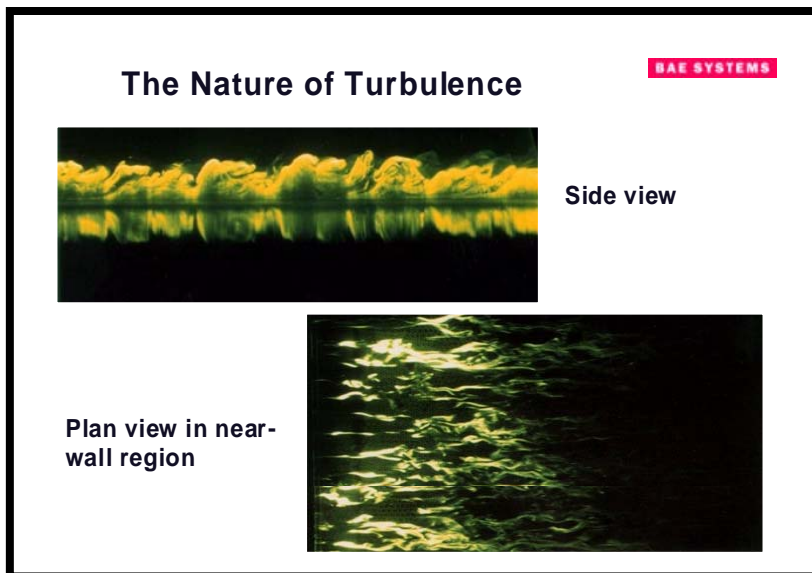
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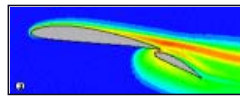
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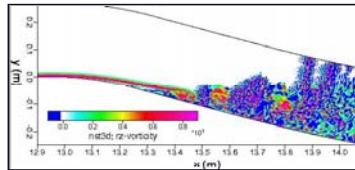


## Large-Scale Eddy Structures

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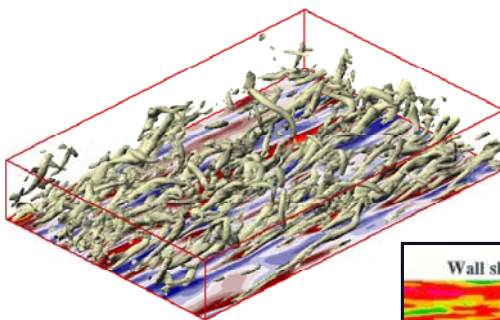
Application to high-lift trailing-edge separations



Excite interaction between large-scale span-wise eddy structures that occur close to point of separation.

## Near-Wall Coherent Structures

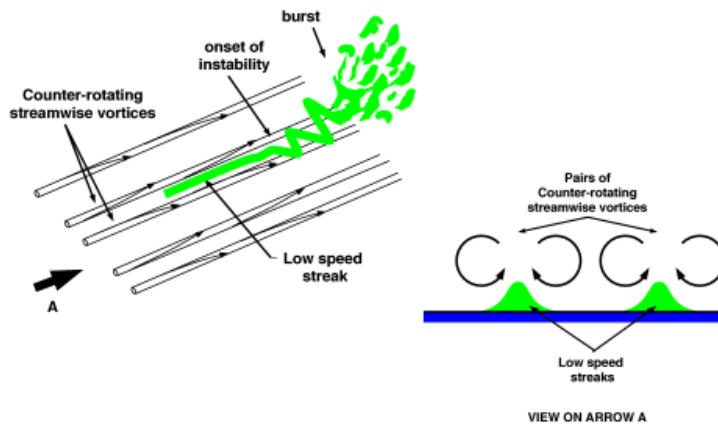
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Wall skin friction at the wall

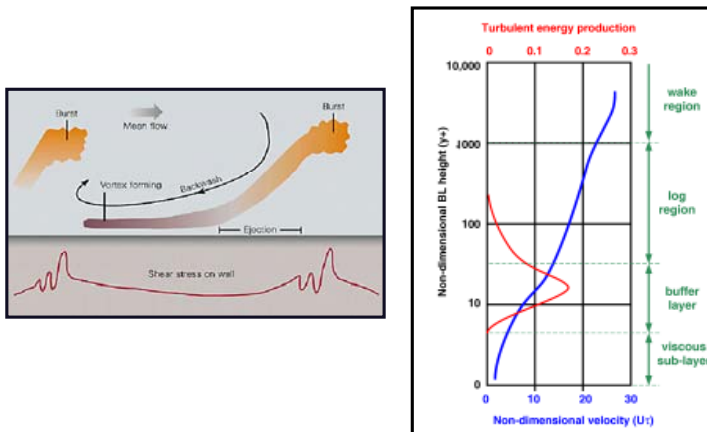
## Near-Wall Coherent Structures

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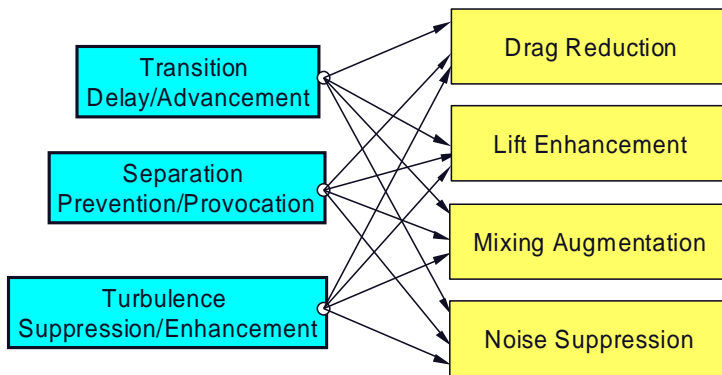
## Turbulent Energy Production

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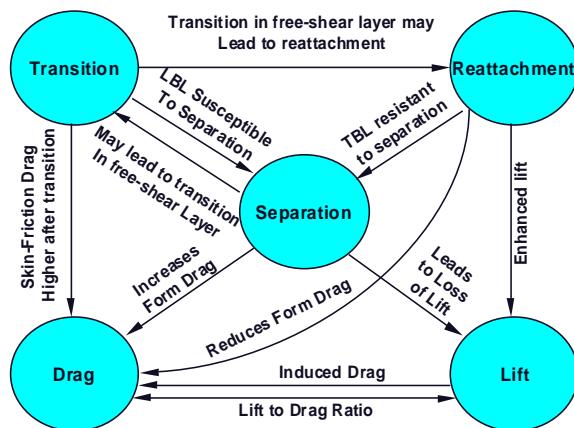
## Engineering Objectives

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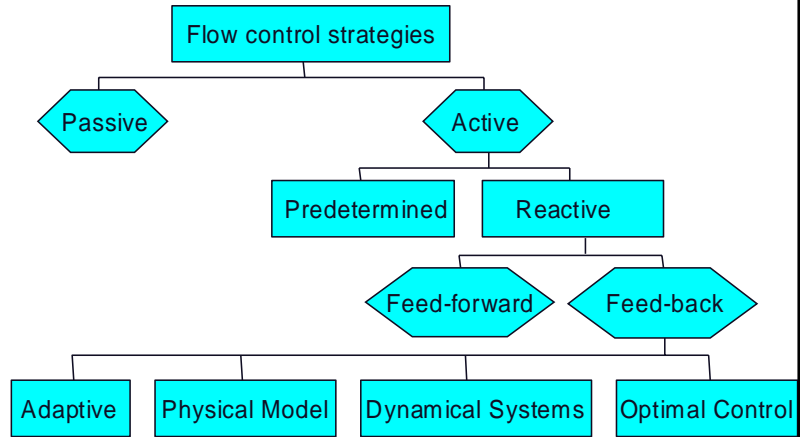
## Relation Between Flow Control Objectives

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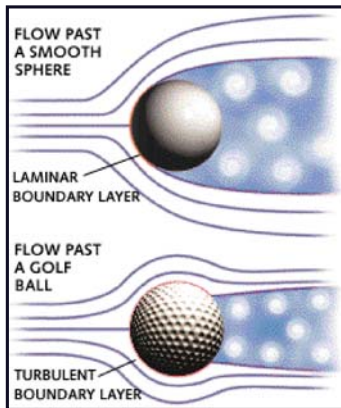
## Classification of Control Strategies

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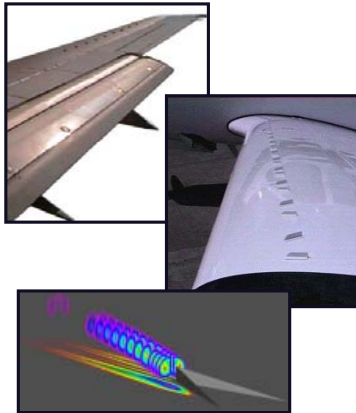


## Passive Separation Control

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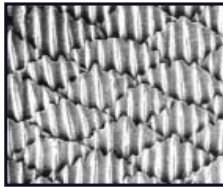
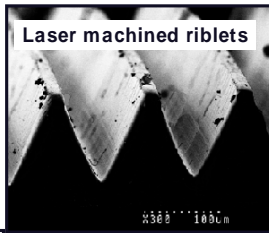
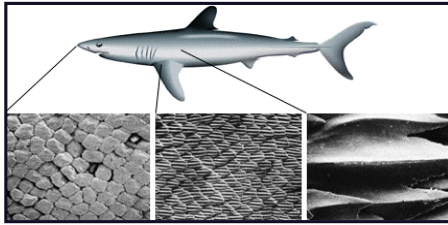
Dimples on a golf ball



Vortex Generators

## Passive Drag Reduction

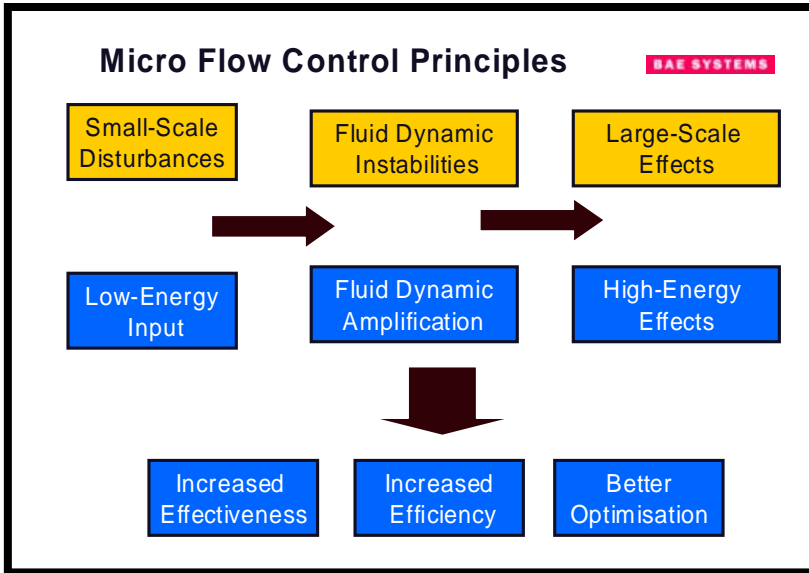
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## Characteristics of Classical Flow Control

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- Passive
  - Riblets, vortex generators
  - Always there - parasitic penalties
- Addition of energy
  - Steady blowing/suction
- Low technology
- Not necessarily fully optimised




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## Opportunities for MEMS Based Flow Separation Control

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**Propulsion and LO Propulsion Integration**

- Inlet distortion
- Pressure recovery
- Flow unsteadiness
- External / internal lip separation
- Compressor stall/surge

**The Benefits**

- Improved Performance
- Improved LO
- Reduced System Complexity/weight
- Increased Design Freedom

**Leading Edge Control**

- Boundary layer and vortex control
- High lift
- LO manoeuvre/stability
- Buffet

**Trailing Edge Control**

- High lift
- Manoeuvre

Low level periodic forcing modulates vortex rollup

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## Application Opportunities

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Micro aircraft



### Airframes

- Manned
- Rotorcraft
- UAVs
- Missiles

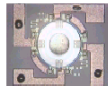


### Propulsion

- Intakes
- Fans
- Compressors
- Combustors?
- Turbines?

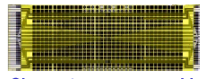
## MEMS Flow Sensors

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Pressure sensor

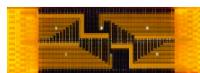
Whole-field sensing  
Spatial-temporal evolution



Shear stress sensor skin



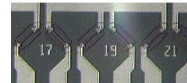
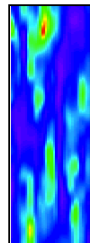
1 M Hz Hot-wire  
⇒ Velocity



Backside contact sensor skin



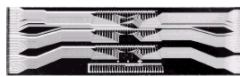
0.02°C Temp. sensor



V-shape  
shear stress sensor array



Shear stress sensor



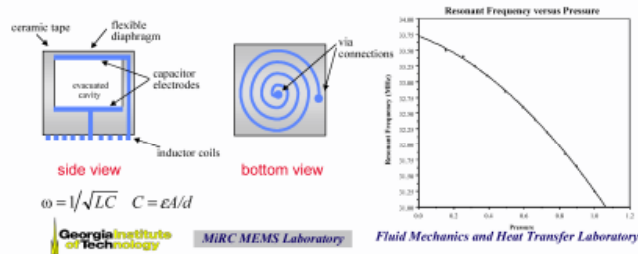
Shear stress sensor array

Sensor array

## High Temperature Pressure Sensor

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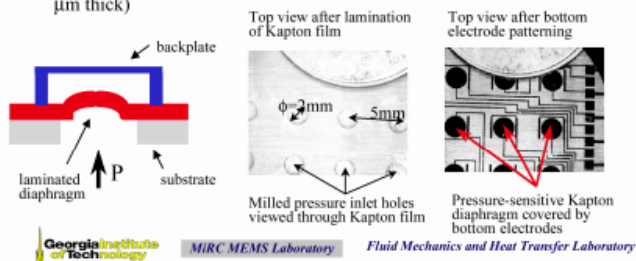
- A silicon diaphragm combined with a ceramic laminate approach and remote readout for sensing high temperatures in turbine engine compressors.
- As the pressure increases, the capacitance increases and the resonant frequency decreases.
- Resonant frequency is read out by determination of the impedance of an external loop antenna---no wiring and power supply is required.



## Metal Surface Pressure Sensor

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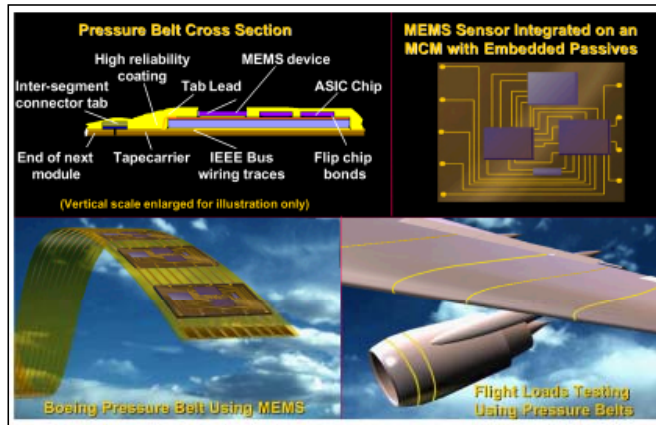
- A stainless steel/metal/organic laminate approach combined with surface micromachined electroplated structures for external aerodynamic applications
- Capacitive pressure sensor (monitor capacitance between diaphragm and surface micromachined backplate)
- Materials: *Substrate*: stainless steel (20 mil); *Pressure membrane*: Kapton polyimide film (2 mil); *Backplate*: electroplated nickel (approximately 15 μm thick)





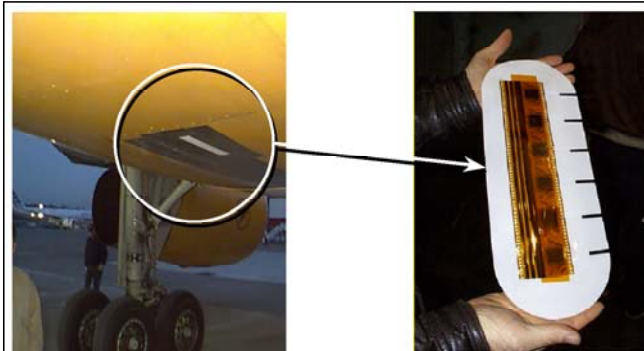
## Boeing/Endevco Pressure Belt

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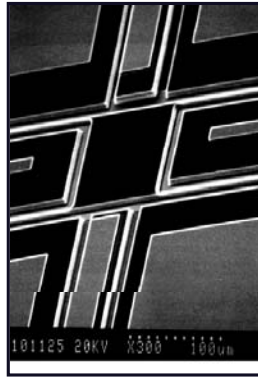
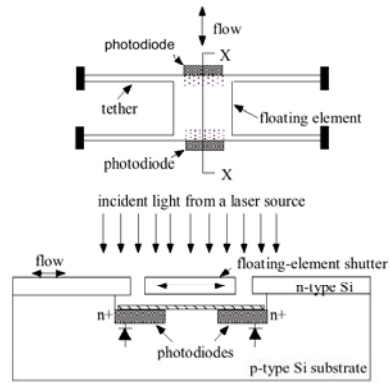
## Boeing/Endevco Pressure Belt

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**Boeing MEMS Pressure Belt  
on Belly Tank of 737**

## Floating Element Shear-Stress Sensor BAE SYSTEMS



Schematic of the Optical Floating-Element Shear Stress sensor (Padmanabhan *et al.*).

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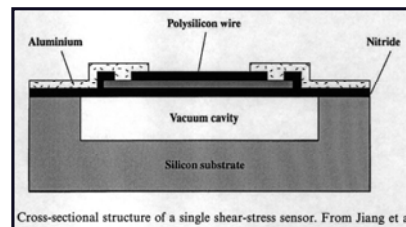
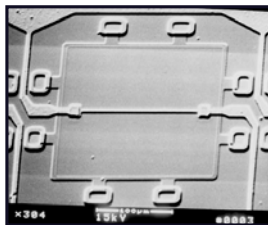
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## Thermal Wall-Shear-Stress Sensors BAE SYSTEMS



Cross-sectional structure of a single shear-stress sensor. From Jiang *et al.*

Sensing element 150 microns long, 10 microns wide

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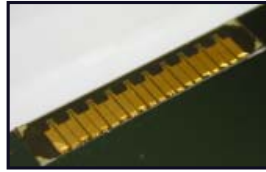
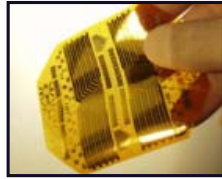
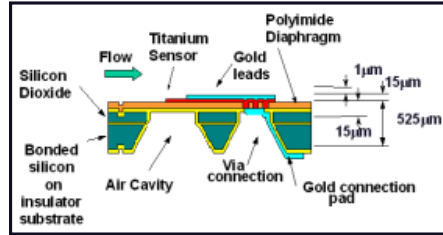
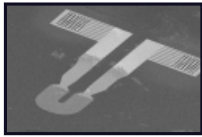
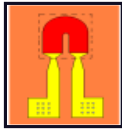
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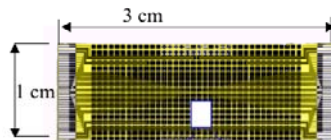
## MEMS Hot-Film Flow Sensors

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## Flexible Hot-Film Gauge Arrays

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\* 72 sensors in 1x3 cm<sup>2</sup> area.

\* Frequency response: 10 kHz

\* Thickness: 80 µm



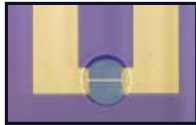
200 x 200 µm<sup>2</sup>



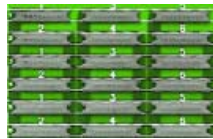
Sensor Skin

## MEMS Flow Actuators

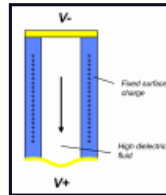
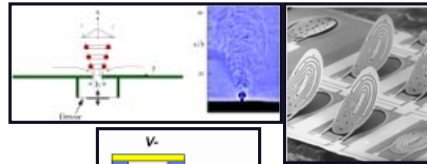
BAE SYSTEMS



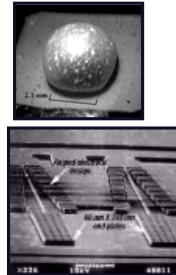
Thermal



Electro-hydrodynamic



Momentum injection




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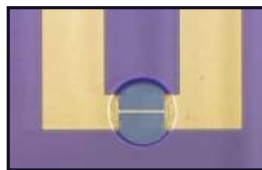
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## Thermal Actuators

BAE SYSTEMS

- Add heat to fluid
- Actuation effects:
  - Density change (gases)
  - Viscosity change (Opposite effects for gasses and liquids)
- Advantages
  - Extremely simple
  - No moving parts
- Disadvantages
  - Thermal loss to substrate
    - Inefficient
    - Lowers bandwidth




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## Momentum Injection Actuators

BAE SYSTEMS

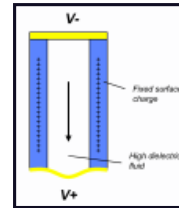
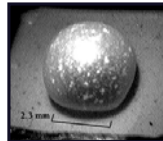
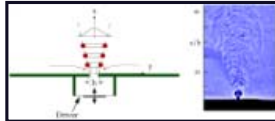
### More direct control authority

- Surface displacement
- Velocity
- Vorticity



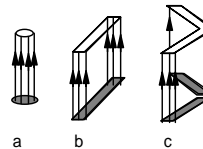
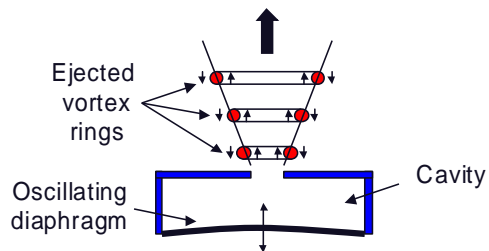
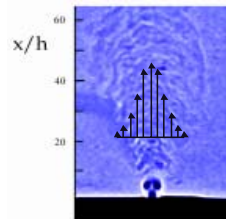
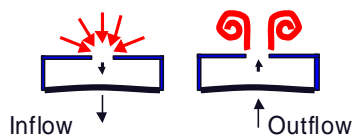
### Many varieties

- Surface motion (normal/lateral)
- Fluidic injection Blowing/ suction
- Direct momentum injection (synthetic jets)



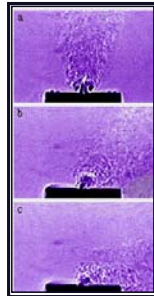
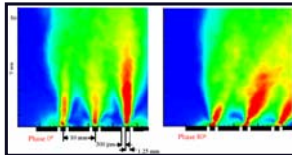
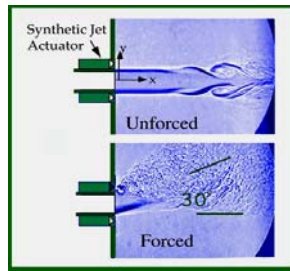
## Synthetic-Jet Actuators

BAE SYSTEMS

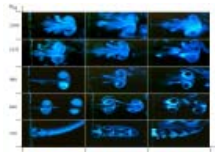


## Characteristics of Synthetic-jets

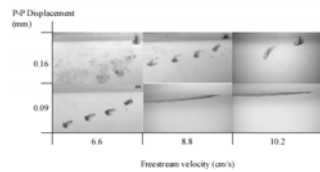
BAE SYSTEMS



Increasing jet velocity



Increasing orifice length



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**BAE SYSTEMS**

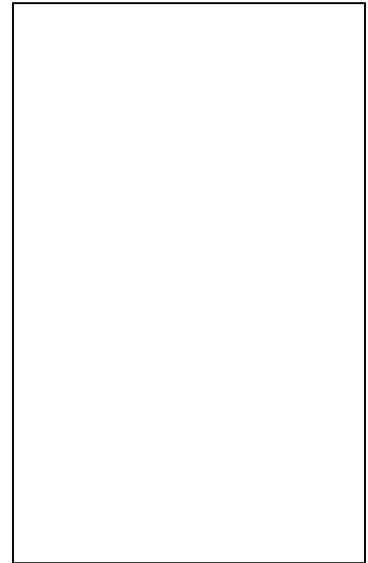
# RTO

**AVT Lecture Series 235**

MEMS Aerospace Applications

## Micro Flow Control (2)

Dr. Clyde Warsop



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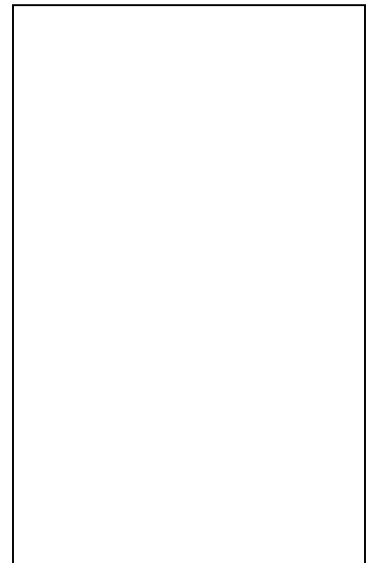
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### Lecture Outline

**BAE SYSTEMS**

- Examples of Research
  - Flow Separation
  - Vehicle Manoeuvre
  - Airframe and Turbomachinery Applications
  - Micro Cooling
- Implementation Issues
- Conclusions and Outlook



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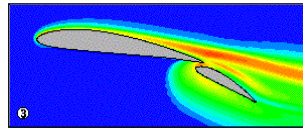
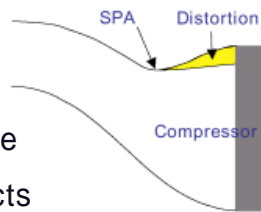
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## Consequences of Flow Separation

BAE SYSTEMS

- Limits maximum lift
- Increased pressure drag
- Unsteadiness  $\Rightarrow$  buffet/fatigue
- Flow distortions/losses in ducts
- limits compressor stall/surge margins



## Benefits of Flow Separation Control

BAE SYSTEMS

- Increased performance (higher, faster, further, more agile)
- Reduced cost (arise from reductions in weight & size, reduced mechanical system complexity, reduced maintenance costs, reduced fuel burn)
- Reduced size (directly related to weight and cost, also benefits reduced signature)
- Reduced weight (directly related to size & cost)
- Reduced maintenance costs (simpler, modularly maintainable MEMS systems could be cheaper than conventional high-lift and control devices)
- Reduced signatures (replace conventional stabilising and control surfaces (eg tail and fins) to reduced RCS, increased mixing of engine exhausts leading to reduced IR signatures)



## Strategies

RAE SYSTEMS

for the wall  
enhance mixing with

structures to increase  
events

structures to  
storing events

erators (where BL is

eddy structures in the

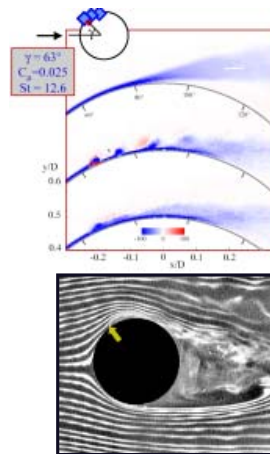
Condition  
BL before  
separation.

control BL at  
separation.

S

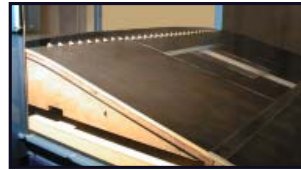
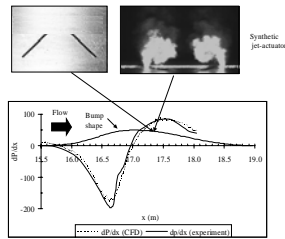
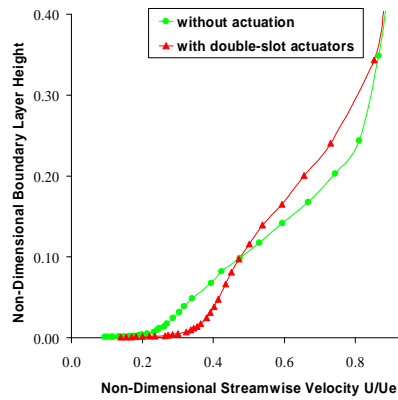
## Control

RAE SYSTEMS



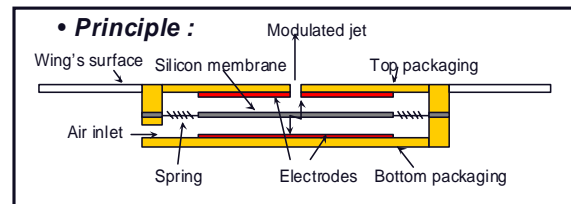
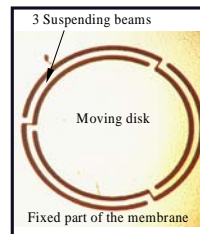
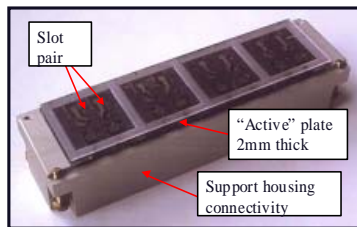
## Synthetic/pulsed Jets for Separation Control

BAE SYSTEMS



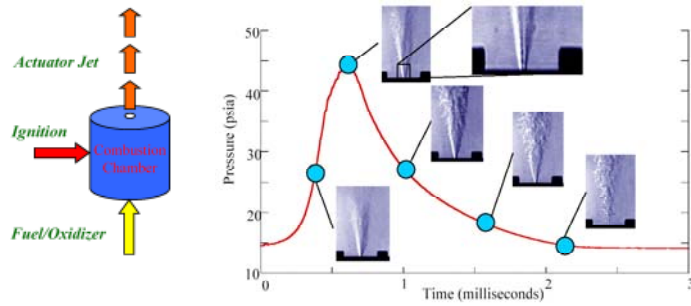
## MEMS Pulsed-Jet Actuator

BAE SYSTEMS



## High Momentum Combustion Actuator (Georgia Tech)

BAE SYSTEMS



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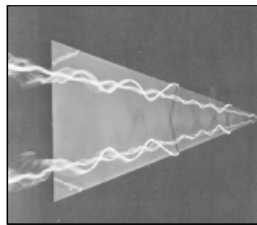
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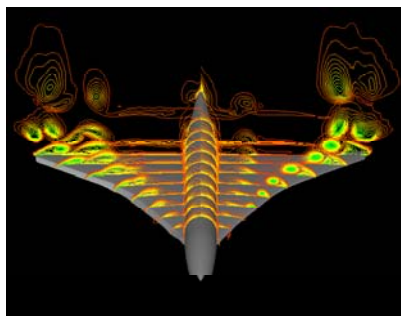
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## Leading Edge Vortex Control (UCLA)

BAE SYSTEMS



Leading edge vortices contribute up to 40% lift



Small changes to vortex strength/position



significant changes to loads and hence lift/control forces

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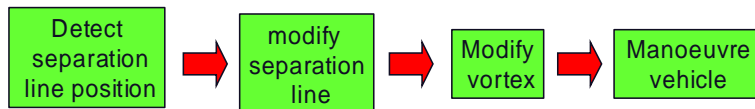
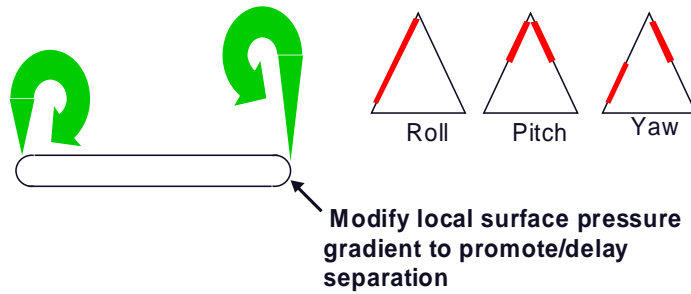
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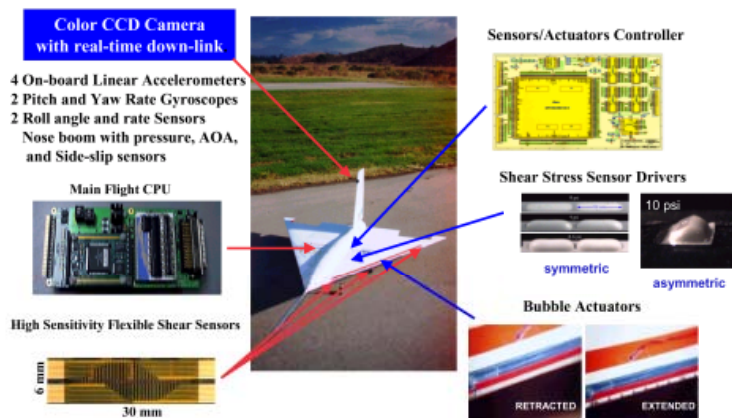
## Leading-Edge Vortex Control

BAE SYSTEMS



## Gryphon MEMS Controlled UAV (UCLA)

BAE SYSTEMS



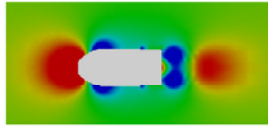
## MEMS to Control Smart Projectile

BAE SYSTEMS

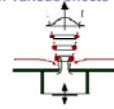
### MEMS Flight Control for Projectiles

ARL Computational Fluid Dynamics Codes

- Understand basic aerodynamic characteristics for flow control
- Investigate "where" jets could be placed for various effects

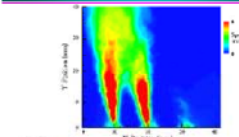


Pressure Contours  
40mm Grenade,  $M = 0.25$



Expanded View of Synthetic  
Jet from GaTech

PIV Data of Modulated Microjet Array



40mm HE/PD M203  
Weapons and Materials  
Research Directorate

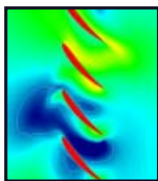


Approved for Public Release - Distribution Unlimited

MEMS at ONR 3-2005 3000-24

## Turbomachinery Applications

BAE SYSTEMS

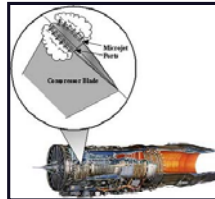


### Intake Duct

- Inlet distortion
- Pressure recovery
- Stall/Surge
- High Cycle Fatigue
- Noise

### Compressor/fan

- Stall/Surge
- Rotating stall
- High Cycle fatigue
- Noise
- Blade tip clearance

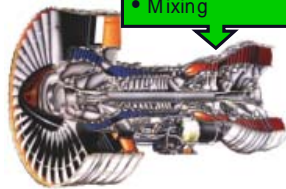


### Combustion

- Mixing

### Turbine

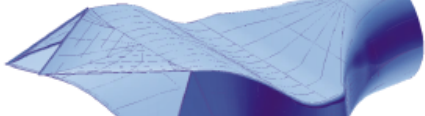
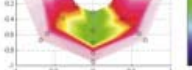

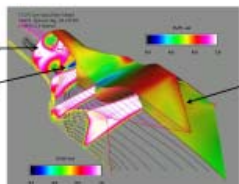
- Efficiency

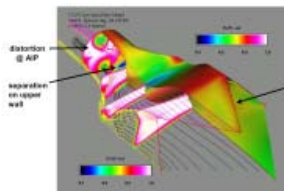
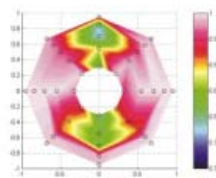


## BAE SYSTEMS



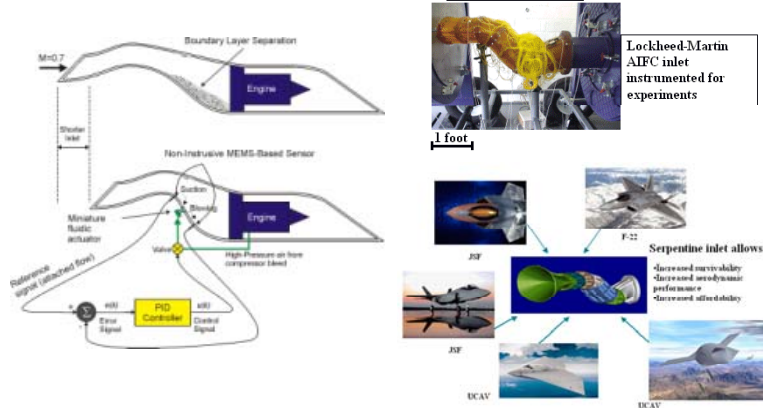
## BAE SYSTEMS

- Worsens adverse pressure gradient on upper and lower surfaces
- 
- 
- 
- 
- Distortion @ AP
- separation on upper wall
- 'clean' flow at exit



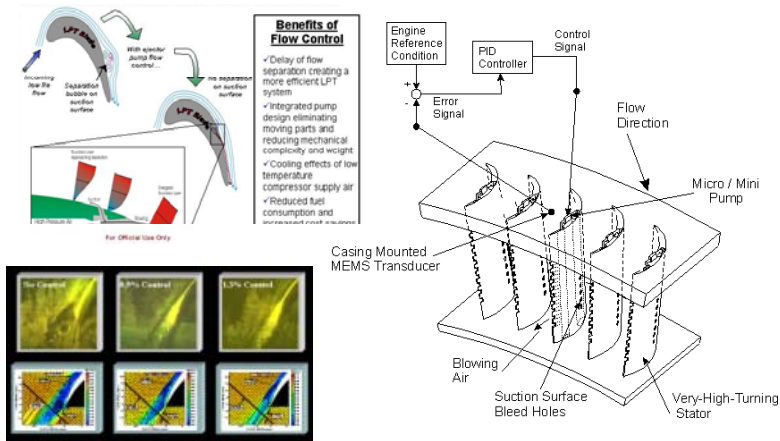
## Separation Control in Intake Ducts

BAE SYSTEMS



## Separation Control on Cascade

BAE SYSTEMS

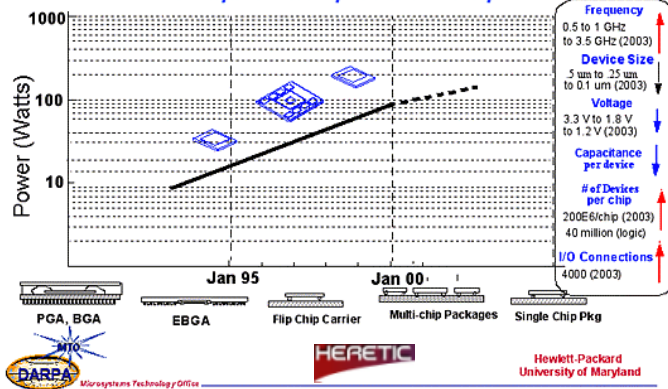


## Micro Fluidic Coolers

### High-performance Chip Dissipation

BAE SYSTEMS

Example: Microprocessor Chips

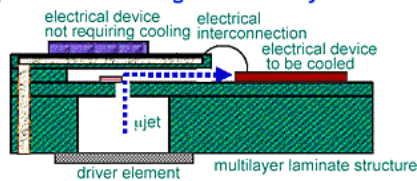


## Microjet Cooling of Electronics

BAE SYSTEMS

### The Active Cooling Substrate (ACS)

Concept: Embed cooling functionality in substrate



- ♦ Microjet arrays
  - » investigations of flow mechanisms
  - » interaction with solid surfaces
- ♦ Driver technologies for ACS
  - » low-frequency membranes
  - » integration approaches
- ♦ ACS fluidic passages
  - » lithography approach
  - » lamination approach
- ♦ Thermal test surfaces
  - » heaters and sensors for spatial cooling assessment



Microsystems Technology Office

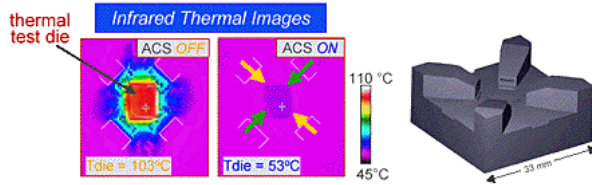


## Microjet Cooling of Electronics

BAE SYSTEMS

### Active Cooling Substrate

- Cooling with quad-jet configuration
  - Opposite jets operate simultaneously
  - Jet pairs operate out of phase



- Maximum power dissipated w.o. cooling  $P_0 = 0.67\text{ W}$
- Power dissipation *increase with microJet cooling*  $\Delta P/P_0 = 220\%$
- Jets flow rate 0.27 cfm



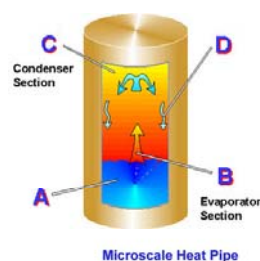
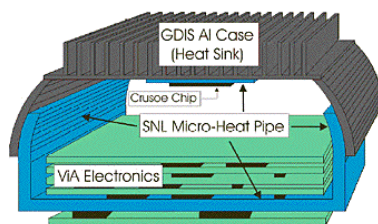
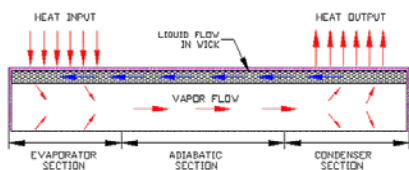
Microsystems Technology Office

HERETIC

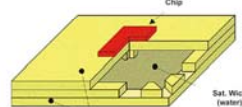
Georgia Tech

## Micro Heat Pipe Cooling Systems

BAE SYSTEMS



Microscale Heat Pipe



HERETIC



Microsystems Technology Office

## Robustness Considerations

BAE SYSTEMS

- Traditional MEMS remote from environment
  - Single or small arrays
  - Hermetic packaging
- Flow control  $\Rightarrow$  must interact directly
  - Harsh environments
  - Reliability
  - Maintenance & repair
  - Safety and certification
  - Large arrays of integrated devices
- Severe implications on design and packaging

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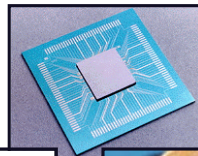
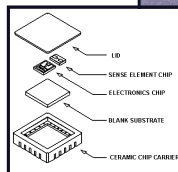
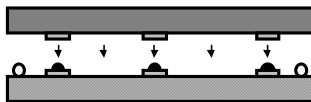
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## Packaging

BAE SYSTEMS

- Science/art of establishing interconnections and operating environment
- Affects: Cost, Performance, Reliability
- Up to 80 - 95% of Cost
- Unique for each application
- Product "Make or break"



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## Conclusions

BAE SYSTEMS

### ■ First Industrial Applications of MEMS

- Limited numbers of sensors and actuators
- Cover small, localised surface areas
- Limited intelligence (simple on-off)
- Flow separation (manoeuvre, or high lift improvement)
- Small UAVs

### ■ Substantial advances required to achieve large surface area reactive skins

- Fluid physics
- Process technologies to fabricate devices that are:
  - Robust, Affordable, Reliable

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